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CHAPTER 6. ON SELECTING THE EXCESS TEMPERATURE
TO MINIMIZE THE ENTRAINMENT MORTALITY RATE

THE COMMITTEE ON ENTRAINMENT

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I. INTRODUCTION

In selecting an excess temperature at which to operate a
power plant cooling system it has been customary to consider only
thermal stresses and to use the ratio of the number of organisms
killed to the number of organisms entrained. This frequently
leads to the selection of a low excess temperature, ΔT, which, in

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turn, requires a large volume flow of cooling water. When
mortalities due to *physical* and *chemical stresses* are included
and the total number of entrained organisms killed is taken as
the measure of the environmental damage, it becomes evident that
the choice of a low excess temperature is seldom, if ever, best.

The fundamental concept is that the lower the excess
temperature to be maintained, the greater must be the volume rate
at which water is taken into the system. More organisms are
entrained and exposed, not only to the thermal stress, but to
physical and chemical stresses as well.

Each power plant draws its cooling water from a different
environment which changes with space and time. Each plant
operates according to its own doctrine. In spite of these
individual differences there are some general characteristics
which hold for all.

(1) The smaller the intake volume rate, the smaller is the
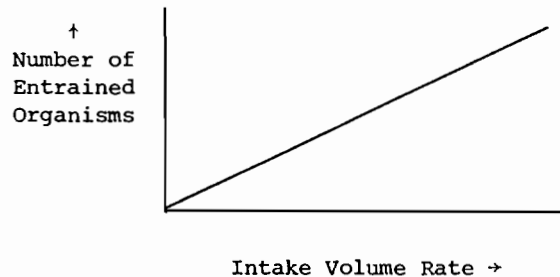number of organisms entrained.

Number of
Entrained
Organisms

Intake Volume Rate →

*Fig. 1. Variation of number of entrained
organisms with intake volume flow rate.*

(2) The smaller the intake rate, the larger is the excess
temperature ΔT.
(3) The lower the excess temperatures, the lower is the
thermal mortality. For any initial intake water

increasing excess temperature. The real reason should
be obvious. At higher excess temperatures the reduced
flow entrains fewer organisms that can be attacked
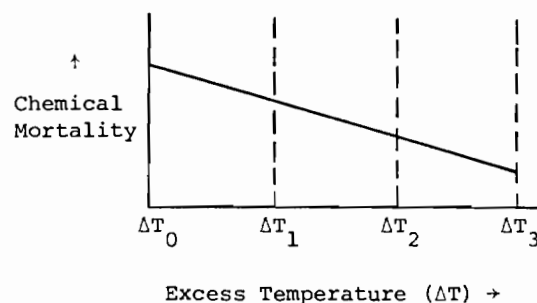chemically.

Fig. 5. *Variation of number of entrained
organisms killed by chemical stress with excess
temperature (ΔT).*

In order to find a criterion for the selection of an
operating ΔT least damaging to the biota it is necessary to
assemble Figs. 2 through 5 in a single model.

II.   THE ENTRAINMENT MORTALITY RATE AS A FUNCTION OF EXCESS
      TEMPERATURE

The measure of the damage done to the biota by a cooling
system will be the *entrainment mortality rate R* defined as the
number of organisms killed per unit time. Contrast this to the
often used *entrainment mortality fraction f* which is defined
as the ratio of the number of organisms killed to the number
entrained in the system. Note particularly that, if one wants
to reduce the damage to the biota, it is R, not f, which must be
minimized.

Let E be the rate at which organisms are entrained by the
system. Then

$$R = fE \quad . \tag{1}$$

Let η be the density of organisms in the water exposed to the intake and Q be the volume rate of intake. Then, in terms of Q, the entrainment rate E is

$$E = \eta Q \quad . \tag{2}$$

The relation between the rate at which heat is required to be expelled H and the volume flow rate of coolant Q required for any excess temperature ΔT, is given by the familiar formula:

$$Q\{\Delta T\} = (\Delta T)^{-1}(H/\rho c_p) \tag{3}$$

where $\rho \equiv$ coolant density

and $c_p \equiv$ the specific heat of the coolant.

Let

$$(\eta H/\rho c_p) \equiv K \quad . \tag{4}$$

K characterizes the plant through the necessary heat disposal H, the coolant through its density ρ and heat capacity c_p, and the biological state through the organism density η. It will vary from plant to plant and from season to season. K is necessarily positive.

Substituting Q from (2) and K from (4) in (3) we have the relation between the entrainment rate E and the excess temperature ΔT.

$$E = K(\Delta T)^{-1} \quad . \tag{5}$$

The mortality fraction has three causes: thermal, physical, and chemical. We will identify them by subscripts.

$f_t \equiv$ the part of f due solely to thermal stress,

$f_p \equiv$ the part of f due solely to physical causes,

and $f_c \equiv$ the part of f due solely to chemical stress.

If one is an optimist, the mortality fractions have corresponding

survival fractions, s:

$$s \equiv 1 - f$$

$$s_t \equiv 1 - f_t$$

$$s_p \equiv 1 - f_p$$

$$s_c \equiv 1 - f_c$$

The s's and f's may, if you choose, be thought of as probabilities of life or death.

For an organism to survive passage through the system it must survive all three kinds of stresses:

$$s = s_t s_p s_c$$

or in terms of mortality fractions

$$f = 1 - (1 - f_t)(1 - f_p)(1 - f_c) \quad .$$

Expanding,

$$f = f_t + f_p + f_c - f_t f_p - f_{tc} - f_p f_c + f_t f_p f_c \quad .$$

All the f's lie between 0 and 1 and not more than one of them can be as large as 1. Therefore if we may neglect the second- and third-order products in comparison with the first-order terms we may write

$$f \approx f_t + f_p + f_c \quad ,$$

without modifying the qualitative relationships of interest for this discussion. The fractional mortalities depend on the excess temperature--directly and obviously for f_t, indirectly for f_p and f_c. It will be well to indicate this functional dependence on ΔT in the usual way by writing

$$f\{\Delta T\} \approx f_t\{\Delta T\} + f_p\{\Delta T\} + f_c\{\Delta T\} \quad . \tag{6}$$

Obviously, our analysis neglects higher order interactions, e.g., death due to thermal effects which would not have been fatal had the organism not already suffered non-lethal physical damage. Such higher order considerations will be minor

corrections on the first order analysis and, considering the state of our knowledge and the prospects for its improvement, unlikely to become available soon.

Substituting from (5) and (6) in (1) we have

$$R\{\Delta T\} = K(\Delta T)^{-1}(f_t\{\Delta T\} + f_p\{\Delta T\} + f_c\{\Delta T\}) \qquad , \qquad (7)$$

the entrainment mortality rate as a function of excess temperatures. It is the minimum value of R which determines the best operating excess temperature--the one least damaging to the biota.

III. SUBRANGES OF THE OPERATING RANGE AND THE BEHAVIOR OF THE MORTALITY FRACTIONS

We have already suggested from an inspection of the thermal mortality curve, Fig. 3, that the range of ΔT has three natural subranges. Let

$(\Delta T_0, \Delta T_3) \equiv$ the full range of excess temperatures.

$\Delta T_0 \equiv$ the smallest possible excess temperature at which it is practical to operate the system. It corresponds to the largest coolant flow and the greatest entrainment of organisms.

$\Delta T_3 \equiv$ the largest possible excess temperature at which it is practical to operate the system. It corresponds to the smallest coolant flow and the least entrainment of organisms.

$(\Delta T_0, \Delta T_1) \equiv$ the subrange of excess temperatures tolerable to entrained organisms. In this subrange $f_t \simeq 0$.

$(\Delta T_1, \Delta T_2) \equiv$ the subrange of excess temperatures in which appreciable, but not total, thermal mortality occurs.

$(\Delta T_2, \Delta T_3) \equiv$ the subrange in which thermal mortality is
substantially total, $f_t \overset{\sim}{=} 1$. In this subrange
there are no survivors, f_p and f_c are
irrevelant, and we may take $f_t = f = 1$.

We can consider the behavior of the mortality fractions within
each subrange.

As shown in Fig. 3, the thermal mortality fraction is
sigmoid.

For $\quad\quad \Delta T_0 \leqq \Delta T \leqq \Delta T_1, \quad\quad f_t\{\Delta T\} \overset{\sim}{=} 0 \quad$;

for $\quad\quad \Delta T_1 < \Delta T < \Delta T_2, \quad\quad 0 < f_t\{\Delta T\} < 1 \quad$;

and for $\Delta T_2 \overset{\leqq}{=} \Delta T \leqq \Delta T_3, \quad\quad f_t\{\Delta T\} \overset{\sim}{=} 1 \quad$.

Over $(\Delta T_0, \Delta T_1)$ and $(\Delta T_2, \Delta T_3)$, $f_t\{\Delta T\}$ is substantially constant
at either 0 or 1. Over $(\Delta T_1, \Delta T_2)$ it is monotonic increasing.

As shown in Fig. 4, the physical mortality fraction, $f_p\{\Delta T\}$,
decreases over the entire range $(\Delta T_0, \Delta T_3)$. Since the higher
excess temperatures correspond to lower flow rates and slower
speeds, less physical damage occurs. $f_p\{\Delta T\}$ is at least monotone
decreasing.

Figure 5 suggests that the chemical mortality fraction,
$f_c\{\Delta T\}$, also decreases over the whole range $(\Delta T_0, \Delta T_3)$. The way
biocides are frequently applied to systems must be considered.
It is customary to inject biocide into a system once daily for
some length of time, to be specific say for one hour. During
injection the chemical is fatal to nearly all the organisms
present. If it were not, it could hardly be called a "biocide."
During the remaining 23 hr the chemical is strongly diluted and
its toxic effects are weak. Thus, the chemical mortality
considered over a day varies with the number of organisms
directly exposed to the biocide pulse. At high excess tempera-
tures volume flow rates are low and so also is the number of
organisms entrained. At low excess temperatures the volume flow
rates are high and so is the number of organisms entrained.
However, since f_c is a fraction of the entrained organisms it

can, at most, be constant on this argument. On the other hand, fewer organisms are exposed to chemical stress at high ΔT than at low ΔT which is a definite gain. What evidence we have suggest that f_c is a monotone decreasing function of ΔT.

The factor $(\Delta T)^{-1}$ is monotonic decreasing over the entire range $(\Delta T_0, \Delta T_3)$.

IV.   BEHAVIOR OF THE ENTRAINMENT MORTALITY RATE ON THE SUBRANGES

Consider $R\{\Delta T\}$ on $(\Delta T_0, \Delta T_1)$. In this subrange f_t is effectively 0 so that (7) becomes

$$R\{\Delta T\} = K(\Delta T)^{-1}(f_p\{\Delta T\} + f_c\{\Delta T\}) \quad .$$

$f_p\{\Delta T\}$ is monotone decreasing.

$f_c\{\Delta T\}$ is monotone decreasing or, at worst, constant.

Therefore, their sum is monotone decreasing.

$(\Delta T)^{-1}$ is monotonic decreasing.

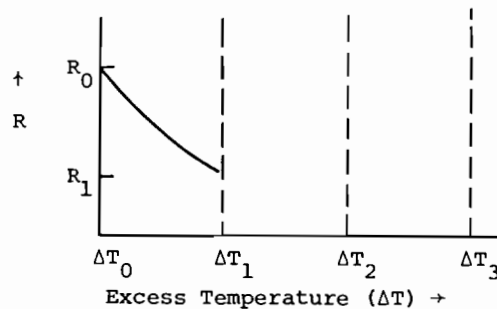Therefore, $R\{\Delta T\}$, which is the product, is monotonic decreasing.

Fig. 6.   Variation of the entrainment mortality rate, R, with excess temperature (ΔT) over the subrange ΔT_0 to ΔT_1. ΔT_0 is the smallest excess temperature at which it is practical to operate a plant. ΔT_1 is the maximum temperature for which mortality from thermal stress is zero.

From this simple argument it is obvious that within $(\Delta T_0, \Delta T_1)$ the most damaging excess temperature at which to run the system is the lowest possible excess temperature ΔT_0. Any other will do less harm and the highest on the subrange, ΔT_1, will do the least.

The situation on $(\Delta T_2, \Delta T_3)$ is equally clear. On this range f_t is substantially constant equal to 1 while f_p and f_c are irrelevant. Equation (7) becomes

$$R\{\Delta T\} = K(\Delta T)^{-1}$$
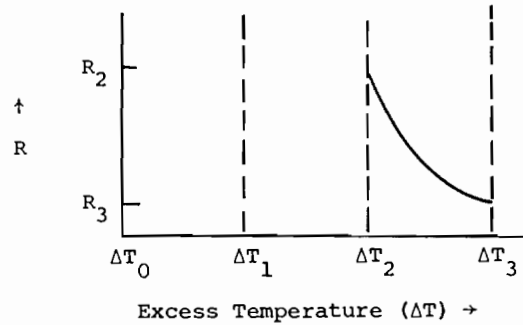
which is monotonic decreasing.

Excess Temperature (ΔT) →

Fig. 7. Variation of the entrainment mortality rate, R, with excess temperature (ΔT) over the subrange ΔT_2 to ΔT_3. ΔT_2 to ΔT_3 is the subrange over which thermal mortality is substantially total. ΔT_3 is the largest excess temperature at which it is practical to operate a plant.

As before, on the interval $(\Delta T_2, \Delta T_3)$ the lowest excess temperature is the most damaging and the highest least.

If only $(\Delta T_0, \Delta T_1)$ is considered, the choice will be ΔT_1. If only $(\Delta T_2, \Delta T_3)$ is considered, the choice will be ΔT_3. If both are considered, further information is needed since we may have $R_1 \lessgtr R_3$. In any case, all other excess temperatures on these intervals are worse and, in particular, ΔT_0 and ΔT_2 are

very bad. The moral is that:

IF YOU WANT TO DO AS LITTLE HARM AS POSSIBLE, DON'T
EVER OPERATE AT A SMALL ΔT.

The situation on the central subrange $(\Delta T_1, \Delta T_2)$ can not
be had by a simple argument. There, f_t is monotone increasing
while f_p and f_c are monotone decreasing. Their sum may be
neither. If the curve positions are as sketched in Figs. 6 and
7, then there must be at least one relative minimum and one
relative maximum in $(\Delta T_1, \Delta T_2)$. It is unlikely that there will
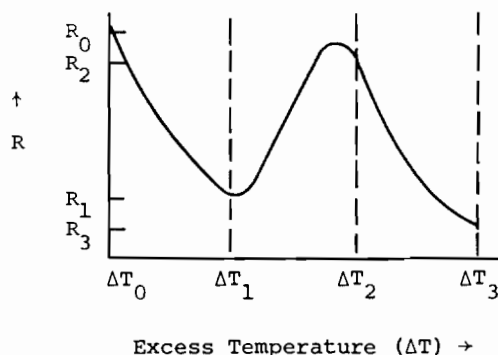be more.

Excess Temperature (ΔT) →

*Fig. 8. Possible variation of the entrain-
ment mortality rate, R, with excess temperature
over the entire range of ΔT, ΔT_0 to ΔT_3.*

On the other hand, Figs. 9 and 10 are also possible, among others.
Only the case with a minimum on $(\Delta T_1, \Delta T_2)$ offers any hope for
an operation excess temperature less harmful than ΔT_1 or ΔT_3. If
a minimum in R exists at $\Delta T_{R_{min}}$, it will certainly be an improve-
ment over ΔT_1. It may or may not be an improvement on ΔT_3.

As our knowledge increases we can hope to improve our
understanding of $R\{\Delta T\}$, particularly on $(\Delta T_1, \Delta T_2)$. As an
immediate practical matter we can reduce damage to the biota by
concentrating on the choice between $R\{\Delta T_1\} \equiv R_1$ and $R\{\Delta T_3\} \equiv R_3$.
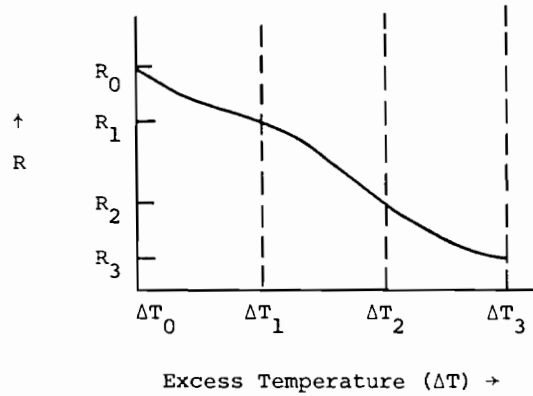
Fig. 9. Possible variation of the entrain-
ment mortality rate, R, with excess temperature
over the entire range of ΔT, ΔT_0 to ΔT_3.

Fig. 10. Possible variation of the entrain-
ment mortality rate, R, with excess temperature
over the entire range of ΔT, ΔT_0 to ΔT_3.
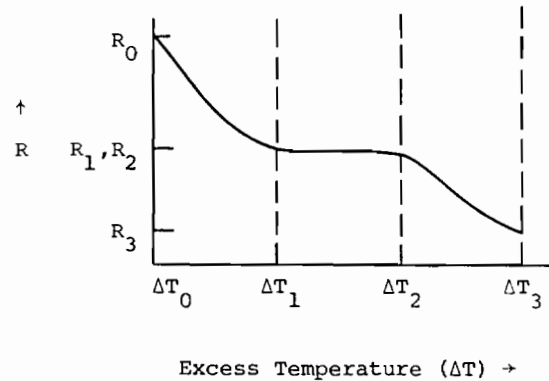
R_1 is certainly an improvement over $R_0 \equiv R\{\Delta T_0\}$ and will be the
chosen excess temperature in the absence of other information.
If $R_3 \equiv R\{\Delta T_3\}$ is also known, then the minimum of R_1, R_3 will
determine the choice between ΔT_1 and ΔT_3.

In brief, only three excess temperatures need be considered:
ΔT_1, $\Delta T_{R_{min}}$, and ΔT_3. Of these, use the one whose R-value is

least. If $\Delta T_{R_{min}}$ is near ΔT_1 while R_{min} is near R_1, inclusion of $\Delta T_{R_{min}}$ in your considerations will not improve much on ΔT_1.

V. THE CRITERION

Application of this analysis in the absence of information calls for using the highest excess temperature at which it is possible to operate the system, ΔT_3. In such circumstances it is true that nearly all organisms passing through the system will die but the number entrained would be greatly reduced thus, one hopes, minimizing the damage to the entire population at risk.

The next higher level of application requires the determination of ΔT_1. The value of ΔT_2, the excess temperature, at which thermal mortality reaches 100% for the first time, is irrelevant unless the highest practical excess temperature, ΔT_3 is less than ΔT_2; which is unlikely. Once you begin killing all the organisms involved the only way to reduce the damage is to reduce their numbers.

To determine ΔT_1 experimental thermal resistance curves, similar to toxicity curves, are needed. They can be expected to be different for different initial (ambient) temperatures, excess temperatures, and durations of exposure before return to ambient temperature as well as for different species and stages of development.

If only organisms of a single species were entrained and that species were the same at each plant, the preparation of thermal tolerance curves would be comparatively easy. As it is, the species composition of the population at risk of entrainment differs from one plant to another and from season to season at any one plant. It is recommended that the thermal tolerance curves be determined for the *Representative Important Species* (RIS). A species may be important for one of three reasons:

(1) It may be commercially or recreationally valuable.

(2) It may be a critical link in the life-web of the region.

(3) It may be a sensitive indicator of the thermal responses of a number of other species.

It would be reasonable to choose for ΔT_1 that excess temperature at which *any* important *sensitive* species developed 10% mortality; the assumption being that few other species would suffer mortalities nearly as high and that most would experience little or no mortality. Other, equally reasonable, suggestions could be made.

Whatever method of choosing ΔT_1 is adopted, it would seem wise to concentrate first on studies of important species common to many plant sites and suspected of having low thermal tolerances.

Once ΔT_1 is known, equation (7) becomes

$$R_1 \equiv R\{\Delta T_1\} = K(\Delta T_1)^{-1}(F_{p,c}\{\Delta T_1\})$$

where

$$F_{p,c}\{\Delta T_1\} \equiv f_p\{\Delta T_1\} + f_c\{\Delta T_1\} \quad .$$

If the organism density at the intake, the heat to be disposed of, and the density and specific heat of the coolant are known, K is known so that the entrainment mortality rate R_1 is known up to a multiplicative factor, $F_{p,c}\{\Delta T_1\}$, dependent on the physical and chemical stresses.

Equation (5) gives us the entrainment rate E as a function of the *excess temperature*. At ΔT_3 all entrained organisms are killed so that E is R and

$$R_3 \equiv R\{\Delta T_3\} \equiv E\{\Delta T_3\} = K(\Delta T_3)^{-1} \quad .$$

Since we want to compare R_1 with R_3 and since they have the common factor, K, a ratio will be useful. Form

$$R_1/R_3 = [K(\Delta T_1)^{-1}(F_{p,c}\{\Delta T_1\})]/[K(\Delta T_3)^{-1}]$$

$$= (\Delta T_3/\Delta T_1)(F_{p,c}\{\Delta T_1\}) \quad .$$

If $\quad (\Delta T_3/\Delta T_1)^{-1}(F_{p,c}\{\Delta T_1\}) > 1$, $R_1 > R_3$ and ΔT_3 is used.

If $\quad (\Delta T_3/\Delta T_1)^{-1}(F_{p,c}\{\Delta T_1\}) < 1$, $R_1 < R_3$ and ΔT_1 is used.

The ratio $\Delta T_3/\Delta T_1 > 1$ while $F_{p,c}\{\Delta T_1\}$ is certainly less than 1 and probably much less.

A simpler way to state the criterion is:

If $\quad \Delta T_3 > F_{p,c}^{-1}\{\Delta T_1\}(\Delta T_1)$ use ΔT_3 .

If $\quad \Delta T_3 < F_{p,c}^{-1}\{\Delta T_1\}(\Delta T_1)$ use ΔT_1 .

We may define an indifference factor by

$$\Delta T_3 = F_{p,c}^{-1}\{\Delta T_1\}(\Delta T_1) \quad .$$

For this value of $\alpha \equiv F_{p,c}^{-1}\{\Delta T_1\}$, $R_1 = R_3$ and it does not matter which excess temperature is used.

TABLE 1   The Indifference Factor

$F_{p,c}\{\Delta T_1\}$	α
0.2	5.00
0.3	3.33
0.4	2.50
0.5	2.00
0.6	1.67
0.7	1.43
0.8	1.25

What Table 1 says is that if you operate a plant at ΔT_1, the excess temperature at which thermal effects just begin to kill, and if at that temperature you are killing 20% of the entrained organisms by physical and chemical stresses then, if your highest possible operating excess temperature, ΔT_3, is more than 5 times as large as ΔT_1, you will kill fewer organisms by killing them all with heat. The bottom line says that if you kill 80% by

physical or chemical stresses before temperature becomes an important killer, then ΔT_3 need be only 1.25 times ΔT_1 before you kill fewer by relying only on temperature.

For fixed heat loss requirement, H, coolant density and heat capacity, ρ and c_p, and density--and composition--of population at risk, η, the "constant" K is constant with respect to ΔT and cancels out of the ratio, $\Delta T_1/\Delta T_3$. However, $K = K(\vec{x},\tau)$, is a function of space and time. If two different plants are to be considered, or the same plant at two different seasons, then a ratio K_1/K_2 will remain. Also, the selection of ΔT_1 depends on the most thermally sensitive Representative Important Species at risk, which may well change seasonally and with plant location. Out of nothing, nothing. Except for the simplest comparisons we should know something about K.

It would clearly be useful to have some experimental information about the mortality fractions due to physical and chemical stresses for the Representative Important Species when ΔT is near ΔT_1. It would appear that, unless a possible $\Delta T_{R_{min}}$ is to be taken into account, this would be sufficient for a fully informed choice. In any case, if ΔT_3 is greater than 5 times ΔT_1, ΔT_1 will be a most unlikely choice.